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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: October 5, 1976

Project Title: A Geophysical Investigation of the Seismicity of the Clark Hill Reservoir Vicinity.

Project No: G-35-622 (Follow-On to G-35-616)

Project Director: Dr. Leland T. Long

Sponsor: U. S. Nuclear Regulatory Commission

Agreement Period: From 9/1/76 Until 8/31/77

Type Agreement: Contract No. AT(49-24)-0210

Amount: $40,957

Reports Required: Quarterly Progress Reports; (Annual) Final Report); Publication Preprints; Publication reprints

Sponsor Contact Person (s):

Technical Matters

Contractual Matters (thru OCA)

Kellogg V. Morton
Research Contracts Branch
Division of Contracts
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Defense Priority Rating:

Assigned to: Geophysical Science (School/Laboratory)

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CA-3 (3/76)

GEORGIA INSTITUTE OF TECHNOLOGY
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SPONSORED PROJECT TERMINATION

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Date: 2/15/78

Project Title: A Geophysical Investigation of the Seismicity of the Clark Hill Reservoir Vicinity

Project No: G-35-622 (Continued by G-35-633)

Project Director: Dr. Leland T. Long

Sponsor: U.S. Nuclear Regulatory Commission; Washington, D.C. 20555

Effective Termination Date: 11/30/77 (thru Mod. 4)

Clearance of Accounting Charges: n/a - Contract continued by Mod. 5.

Grant/Contract Closeout Actions Remaining: None until final year of contract.

- _ Final Invoice and Closing Documents
- _ Final Fiscal Report
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
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NOTE: ORIGINAL CONTRACT THRU MOD. 2 UNDER G-35-616

Assigned to: Geophysical Sciences (School/Laboratory)

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G35-622 NUREG-0009

A GEOPHYSICAL INVESTIGATION OF THE SEISMICITY OF THE CLARK HILL RESERVOIR VICINITY

Quarterly Progress Report No. 7
September 1, 1976 - November 30, 1976

Leland Timothy Long
School of Geophysical Sciences
Georgia Institute of Technology
Atlanta, Georgia 30332

Report Date - December 15, 1976

PREPARED FOR THE U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGUALTORY RESEARCH UNDER
CONTRACT NO. AT-(49-24)0210

A Geophysical Investigation of the Seismicity of the Clark Hill Reservoir Vicinity

Quarterly Progress Report No. 7

Abstract

Seismic monitoring has continued at stations CH5 and CH6 with the addition of partial recording at RF transmitting locations. Spectral studies of events in the CHRA continued with comparison of the data with spectra from events in the Jocassee reservoir area and Maryville, Tennessee. Seismic refraction data are being obtained for two lines extending south on either side of the CHRA from the Richard B. Russell dam site.

Scope of Investigation

To use gravity, seismic refraction and other available geophysical data to study the structures of the crust in the Clark Hill Reservoir Area and to relate the structures to earthquake activity as recorded by a telemetered seismic array or by portable instruments. To initiate seismic monitoring of the Belair fault and seismic activity near Lake Sinclair for similar studies of crustal structure and seismicity.

Results of Investigation During Quarter Quarter

The seismic monitoring has continued without interruption at CH5 (Double Branches in the southern part of the reservoir) and CH6 (Goshen in the northern part of the reservoir). During the quarter, power was supplied to CH6 to allow use of CH6 as a central RF receiving point for the northern portion of the reservoir. Both the low elevation and low seismic activity levels inhibited our use of CH5 as a RF receiving point. Seismic activity determined the choice of four RF transmitting locations. Two (RF1 and RF3) were on the west side of the reservoir and were placed to allow better location of a small swarm of events located 6 km southwest of Goshen. RF2 was located in the epicenter area of the August 1974 earthquake on the South Carolina side of the reservoir. RF4 was located also in South Carolina north of Hickory Knob Park in order to monitor possible activity located neaby that area. Stations RF1 has proved the most reliable. Stations RF2, RF3, RF4 have operated only sporatically.

A publication entitled, "Gravity and Seismic Studies in the Clark Hill Reservoir Area," was published in Guidebook 16 for the September 9-10, 1976 Georgia Geological Society field trip on the "Stratigraphy, Structure, and Seismicity in Slate Belt Rocks along the Savannah River." Six copies (in lieu of reprints) are submitted under separate cover. Also, in response to numerous inquiries, a short summary was prepared to put activity in the Piedmont Province into perspective. Although publication is not anticipated in the present form, a copy is attached as Attachment I for comments if appropriate.

The spectral study of CHRA microearthquakes and a comparison with earthquakes recorded near Jocassee reservoir, South Carolina and Maryville, Tennessee is expected to be complete next quarter. The spectral study of events recorded on portable tape recorders is being prepared as a M.S. thesis by Mr. George E. Marion. Preliminary results indicate corner frequencies above 100 Hertz and a significant difference between events from Maryville, Tennessee and the Georgia-South Carolina Piedmont province.

We have recorded seismic refraction data in order to better define the velocity anomalies and travel time curves appropriate for the area. The primary sources for the data have been blasts at the site of the R.B. Russell Dam diversion channel. Two refraction lines are being attempted; one down the west side of the reservoir including stations CH5 and CH6 and the others down the east side of the reservoir. Unfortunately, the data acquisition is slow since the blasts only occur at the rate of one per week and are largely unscheduled, occurring at all hours of the day.

The U.S. Army Corps of Engineers has undertaken a significant regional study for a design earthquake report entitled, "Geological and Seismological Evaluation of Earthquake Hazards at the Richard B. Russell Project." The report, which will be complete by March, 1977, will include a significant amount of material pertaining to the Clark Hill Reservoir Area. Consequently, the efforts at Georgia Tech will be coordinated with the Corps of Engineers' studies where practical and feasible to avoid duplication and enhance both studies. As part of this effort, an analysis of the maximum induced earthquake was prepared using and summarizing conclusions from the Clark Hill Reservoir Area Study. A copy of the report is attached (see Attachment II).

Progress During Quarter

The project progressed at the scheduled rate during the quarter.

Efforts Expended During Quarter

The principal investigator expended an average of 25% in the project during the quarter. Three graduate students were employed at about 50% time during the quarter. One electrical engineering student was employed at about 30% time during the quarter.

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Long, L.T., H.E. Denman, H.Y. Hsiao and G.E. Marion, (1976). Gravity and seismic studies in the Clark Hill Reservoir Area, in Statigraphy, Structure and Seismicity in Slate Belt rocks along the Savannah River, compiled by T.M. Chowns, Georgia Geological Survey, Guidebook 16.

ATTACHMENT I

MAXIMUM "INDUCED" EARTHQUAKE

CLARK HILL RESERVOIR AREA

SUMMARY

The earthquakes of the Piedmont Province and the Clark Hill Reservoir Area (CHRA) share many distinctive characteristics and do not appear to satisfy conventional tectonic mechanisms involving observable faults. Consequently, an alternate explanation for the earthquake mechanism is proposed which involves stress amplification or strength modification in coherent near-surface geologic units. This mechanism allows a restriction on the size of the maximum plausable earthquake by placing practical limits on the size of the fault.plane and magnitude of the stress drop. The upper limit in size for the fault plane is the 39.5 km^2 implied by microearthquake activity near Jocassee lake. CHRA microearthquakes and geologic units indicate about 10 km^2. The stress drop estimates for these events is consistantly about 6 bars. Using 6 bars and a fault plane of 39.5 km^2 in the relation of Randal (1973) a magnitude 5.6 event is the maximum plausable "induced" earthquake.

MAXIMUM "INDUCED" EARTHQUAKE

CLARK HILL RESERVOIR AREA

INTRODUCTION

Earthquakes in the Clark Hill Reservoir Area share many distinctive characteristics with earthquakes occurring throughout the Piedmont Province of Georgia and South Carolina. A typical event has a depth of focus less than 5.0 km as indicated by the generation of large surface waves and by aftershock studies. Their magnitudes have been less than $M_L = 5.5$ with the Union County earthquake of January 1, 1913 being the largest ($M_L = 5.45$). No coherent active faults have been identified as causitive structures connecting two or more Piedmont Province earthquakes. The earthquakes have occurred primarily as swarms or aftershock sequences in a limited number of discrete epicentral zones. The near-surface geologic units of the Piedmont Province are largely made up of metamorphosed sedimentary and volcanic rocks which have been penetrated by both mafic and granitic intrusives. The resulting complexity in geologic structures allows a significant heterogeniety in physical properties of the near surface rocks while also allowing highly competent rocks to occur within a few hundred feet of the surface. Because of these common characteristics, the earthquakes all probably share a common explanation which can be expressed in terms of the causitive stresses and the near-surface geologic structures.

The fundamental explanation for crustal stresses which cause earthquakes in the Piedmont Province is not currently understood completely, largely because of a lack of data. The conventional explanation of earthquakes in terms of continued movement along existing faults is not supported by existing data. In order to explain the earthquakes in the Piedmont Province, Long (1976) proposed an alternate mechanism of stress amplification by shear modulus inhomogenieties near the surface. In stress amplification, the geometry of anomalously rigid structures cause the amplification of applied or residual stress. To acheive stress large enough to cause earthquakes, first a structure with appropriate geometry must exist, second the structure must consist of a material with anomalously high rigidity and/or low strength and third a stress must be applied (or the strength changed) in a direction appropriate to cause stress amplification. The origin of the causitive stress is probably the result of a combination of factors. Because of the thickness of the Piedmont Crust (35 to 40 km) and the relatively smaller size of most near surface inhomogenieties (less than 5 km), crustal flexure probably contributes only slightly to the ambient stress field. Near-surface factors such as unloading through weathering, inhomogeneous stream erosion, and strength modification through weathering or fluid penetration, probably dominate as mechanisms for stress accumulation. With stress amplification or strength modification these could explain Piedmont Province earthquakes.

Some of the Piedmont earthquakes have occurred near reservoirs and their occurrence has been attributed to reservoir loading or fluid pressure effects (see Denman 1974, Talwani, 1976). However, with the exception, perhaps, of the Jocassee reservoir, earthquakes which are located within 10 km of the Blue Ridge Province, the larger events are not directly correlatable in time with the reservoir loading. Many areas which showed activity after loading, like the Clark Hill Reservoir or Lake Synclair, also had a history of seismic activity prior to loading. In the Clark Hill Reservoir area and other reservoirs spacially associated with earthquakes in the Piedmont Province, the earthquakes are not always located near the deepest part of the reservoir as they should be if they were purely reservoir induced. The marginally convincing spacial and time correlation of large events with reservoirs suggests that the reservoir itself may not be responsible for the production of seismic activity through loading. However, the possibility cannot be ruled out that large lake fluctuations or rainfalls act as a catalyst when stress conditions reach levels suitable for the production of microearthquakes. Indeed, the near surface occurrence of events and the hypothesis given above concerning their cause would be compatible with water level fluctuations or rain falls acting as catalysts to microearthquake activity.

If the hypothesized mechanisms given above is assumed to be a correct and exclusive mechanism for Piedmont Province earthquakes, then the establishment of a maximum, plausible earthquake, induced or natural, is possible. The object of this study is to estimate the maximum plausible earthquake to be expected for the Clark Hill Reservoir Area given the mechanism presented above. The first step will be to estimate the largest possible fault plane and the type of movements that might occur. Next the stress drop will be estimated by comparison to similar sized events for which the stress drop has been measured. Stress drop estimates for Clark Hill Reservoir Area microearthquakes will be utilized in the evaluations. Finally, theoretical and observed relations between fault size and stress drop will be used to estimate the local magnitude of a maximum plausible earthquake.

ESTIMATE OF LARGEST PLAUSIBLE FAULT PLANE

Active faults, directly related to contemporary seismic activiety are not known for the Piedmont Province of Georgia and South Carolina. No coherent faults have been identified as causitive structures connecting two or more Piedmont Province earthquakes. Linear allignment of epicenters separated by distance equivalent to the source dimensions of the earthquake have not been observed and would be necessary to hypothesize a fault in the case where a fault would not be observed at the surface. More typically, Piedmont Province earthquakes occur at discrete locations. These locations are separated by distances significantly larger than the dimensions of the earthquake source. Also, if more than one event occurs at one of these discrete locations, the epicenters are not distinguishable with existing teleseismic data. In a few individual earthquakes, the proximity of the epicenter to known faults has prompted speculation concerning the active status of the faults (Talwani, 1976). However, no evidence of recent movement can be observed on these faults and the seismic correlation is weak. All the faults represent movement at a time when the tectonic stresses were significantly different than they are today.

As a consequence of the lack of confirmed active faults, the problem of determining the maximum fault plane requires data from sources other than the geologic mapping of faults. Data on aftershocks of large events are sparse in the Piedmont Province but available for the CHRA and Jocassee lake. These can be used to obtain information on the size of the zone of high stress. The aftershock locations of the August 2, 1974 CHRA earthquakes (Bridges, 1975) indicate a zone of maximum width of 5 km with the majority occurring within a 2 km central zone. More recent data at Georgia Tech indicates that the zone of activity has essentially remained the same (figure 1.0) but the level of activity has decreased. Data on aftershock locations computed by Talwani (1976) indicate the same general distributions. The depth of focus range from near-surface (within 0.5 km) to a maximum depth of focus of 2.0 km (see figure 2.0). Most occurred within 0.5 km of 1.0 km. The area of microearthquake activity associated with the Jocassee area (Fogle et.al., 1976) is significantly larger. Over a period of 3 months the epicentral area grew from 4 km to 9 km in diameter while at the same time the overall activity level was decreasing. The maximum depth observed for

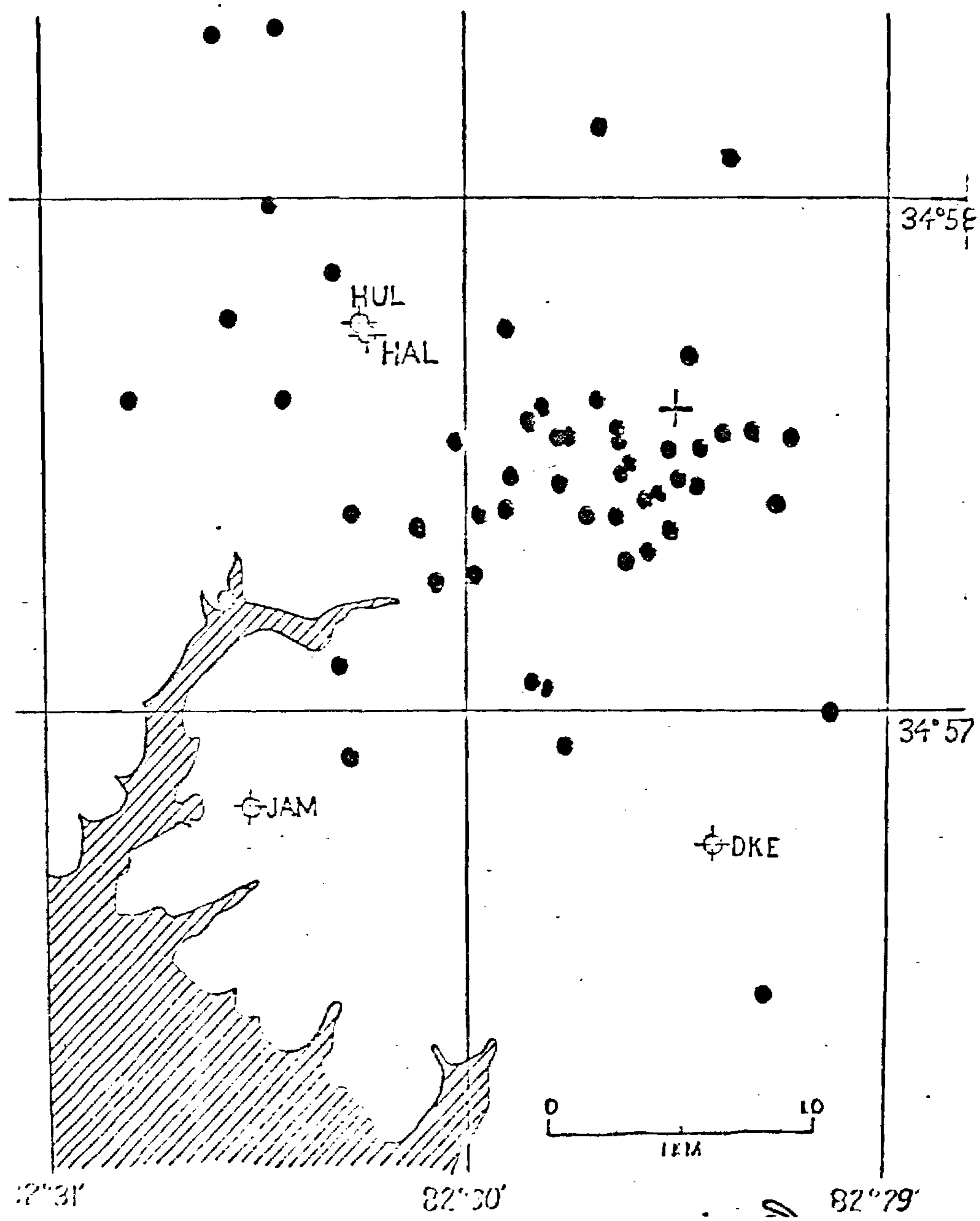

Figure 1. Epicenters for microearthquakes in the Clark Hill Reservoir Area.

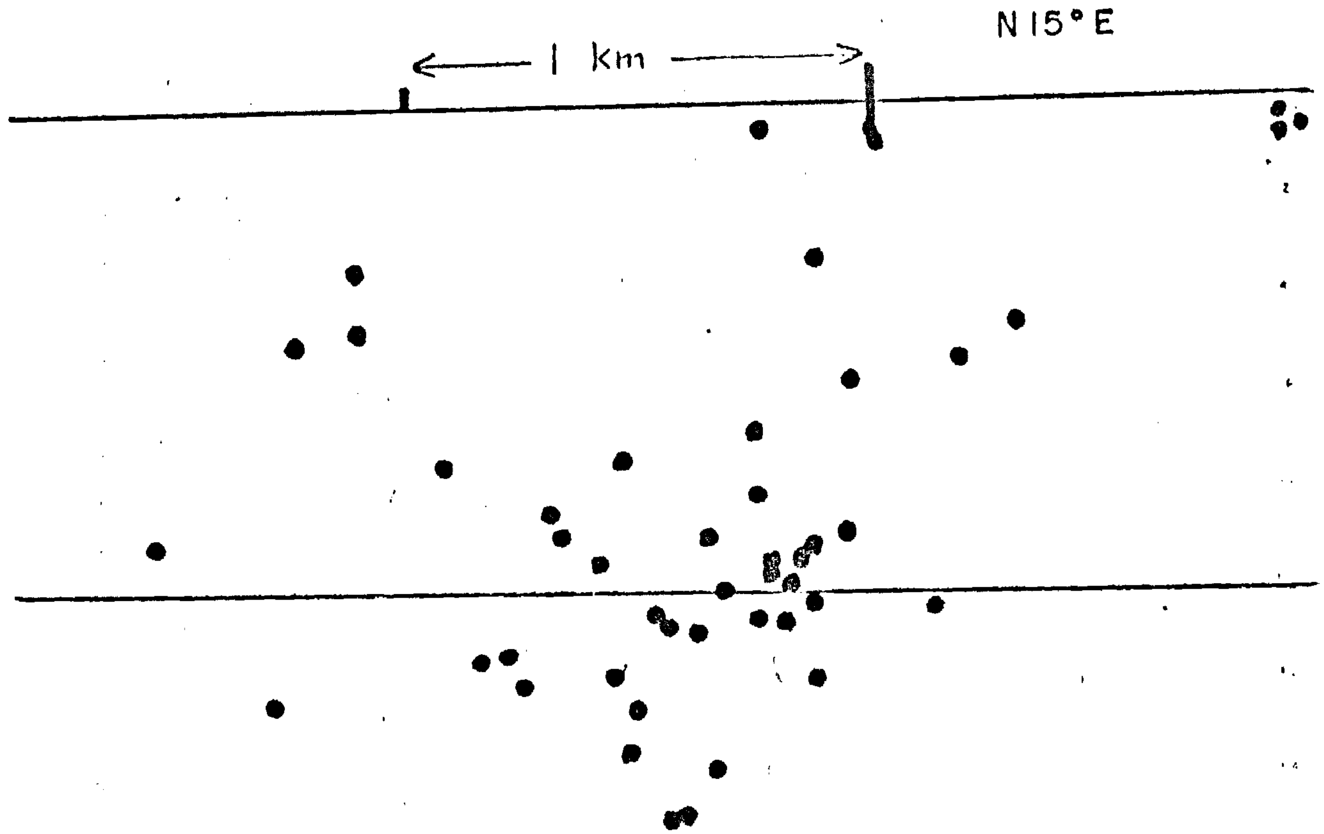

Figure 2. Cross section of hypocenters for events in the Clark Hill Reservoir Area. The hatch mark indicates the position of the cross in

aftershocks was about 4.0 km but significant activity was limited to less than 2.7 km deep.

The observed aftershock location for Piedmont Province earthquakes thus indicate fault planes of 10 km^2 for the CHRA and 39.5 km^2 for Jocassee after correcting for possible dip in the fault plane. There is an apparent discrepancy in the relative sizes of areas in that the largest event in the CHRA was a M_L = 4.8 while the largest event in the Jocassee area was a M_L = 3.2. However, in the Jocassee area the dominant active area at any one time was seldom wider than 2.0 to 3.0 kilometers indicating a lack of stress coherency throughout the area. Focal mechanism studies (Fogle et.al., 1976) indicate discrete epicentral zones of smaller size within the Jocassee area. In conclusion, the largest fault plane from aftershock distributions associated with a discrete event is 10 km^2 in the CHRA and for a composite epicentral zone is 39.5 km^2 in the Jocassee area.

An alternative approach to the determination of the maximum fault plane would be to evaluate dimensions of geologic units potentially related to the seismic activity. In both areas the aftershocks occur generally throughout a volume. At Jocassee, they occur in the Henderson Gneiss above the extrapolated position of the Brevard zone. In the CHRA they occur generally in a mixed gneiss unit corresponding to a negative Bouger anomaly. Hence, by assuming the fault plane to be limited by the dimensions of coherent geologic units an estimate of the largest plausible fault plane can be obtained directly from geologic structures. In the CHRA interpretation of gravity data (Long, et al., 1976) and the Geologic Map of Georgia (1976) indicate geologic units with widths typically less than 6 km with the exception of the Danburg Granite and the Lincolnton metadacite. The Lincolton metadacite however, is probably no thicker than 5 km. Most coherent geologic units are significantly less than 6 km. If these units have effective depths of less than 5.0 km then the largest plausible fault plane areas are about 30 km^2 or still less than the

39.5 km^2 for the Jocassee aftershock zone. The 5.0 km maximum depth estimate exceeds depths computed for any aftershock observed in the Piedmont Province. If a relation between these events and surface water loading exists then the depth of the maximum fault plane may be limited by the porosity of the rocks or the ability of existing joints to allow penetration to depth.

ESTIMATE OF STRESS DROP

The average stress drop along a particular fault plane in material with a given seismic velocity is a measure of the magnitude of the earthquake that will be produced. A high stress drop will give a larger earthquake than will a small or partial stress drop. Hence, the determination of plausible stress drops is an important factor in determining the largest magnitude event that a given fault plane can generate. The seismic velocities are also important because they define the rigidity and with the displacement the stress of the rock near the fault plane. The higher the rigidity, the smaller the displacement for a constant stress drop and fault dimension. The near-surface rocks in the CHRA have p-wave velocities on the order of 5.8 to 6.1 km/sec. These velocities are typical of rocks in the upper 10 km of the crust, below the superficial sedimentary rocks and imply that CHRA displacements computed for events of similar stress drop will be equal to or less than displacements computed for other shallow earthquakes. They also imply conversely that for the same displacement, the stress drops in the CHRA should be greater than or equal to stress drops in other shallow earthquakes. Unfortunately, data or measurement methods to directly determine stress conditions in the crust are not currently available. However, plausible stress drops can be estimated from in situ stress measurements, evaluations of stress drop for continental earthquakes, and computation of stress drops for Piedmont Province or CHRA earthquakes.

In situ stress measurement are not available in the CHRA. Nevertheless, measurements near Atlanta and the Bad Creek site near Jocassee indicate deviatory stresses on the order of hundreds of bars. At shallow depths, 1000 to 2000 bars is significant to cause rupture of fresh rock but it is unlikely that such stresses could exist over an entire fault plane. As indicated by the near-surface measurements, such stresses could exist at locked points along a fault plane or at discontinuities in a fracture surface. However, at distance the seismic waves of an earthquake are primarily determined by averages or effective stress drops distributed over the entire fault plane. Consequently, individual measurements of stress would not be expected to be as meaningful a measure of the average stress drop as would be stress drop estimates based on seismic waves at distance.

Evaluations of stress drops for intraplate earthquakes are limited. The most extensive available evaluation of eastern United States earthquakes (Street et al., 1976) indicated that events of seismic moment greater than 5×10^{23} dyne cm (equivalent to $M_L \geq 4.0$) have a stress drop of 6 bars. The lack of variation is indicative of a similar physical mechanism for the initiation of rupture along a fault. Street et al. (1976) also noted that the spectra from the larger events implied partial stress drop while the smaller events often implied complete stress drop. In commenting on the constant stress drop for large events, Street et al. (1976) suggested that the earthquake process in the region is uniform in contrast to southern California, where a wide range in stress drops occur for events with the same seismic moment.

The stress drop of the August 2, 1974 CHRA earthquake was evaluated by Bridges (1975). He used a variety of theoretical and empirical relations and observed data. The most reliable estimates averaged 5.0 bars and varied by only $\pm$ 1.0 bar. The theoretical estimates are based on the magnitude (M_L)

and fault areas estimated from the spectra and from the aftershock zone. The empirical methods (from Gibowicz, 1973) are based on aftershock "b" values and the difference in magnitude between the main shock and the largest aftershock. The normal stress drop (after Gibowicz, 1973) for a magnitude 4.8 event was given as 0.74 bars indicating that the stress drop for the CHRA earthquake of August 2, 1974 was anomalously high. The high stress drop is consistent with the implications of the high near-surface rigidity of the Piedmont Province, the lack of observed movement along existing faults and the mechanism of stress amplification in near surface geologic units.

Recent spectral data from the CHRA (Marion, 1977) indicates that the largest stress drop for microearthquakes was 7 bars. Furthermore, the spectra indicate transsonic rupture velocities and, consequently, a minimal frictional stress along the fault plane. These characteristics are indicative of a near-tensional stress condition which would be susceptable to perturbation by ground water pressure variations.

Plausible stress drop based on these date would be 5 to 7 bars. The data are remarkably consistent and no data in the Piedmont Province exists to indicate that higher stress drops exists.

LOCAL MAGNITUDE (M_L) FOR MAXIMUM EARTHQUAKE

In a consideration of the spectral theory of seismic sources and a comparison of the theory to spectral data, Randal (1973) developed a relation between Local Magnitude (M_l) fault dimension and stress drop. The relation was shown to be consistant for a large range of observed data. Figure 3 shows this relation modified for the generally observed stress drop of eastern United States and the Piedmont Province of 6 bars. The maximum fault planes

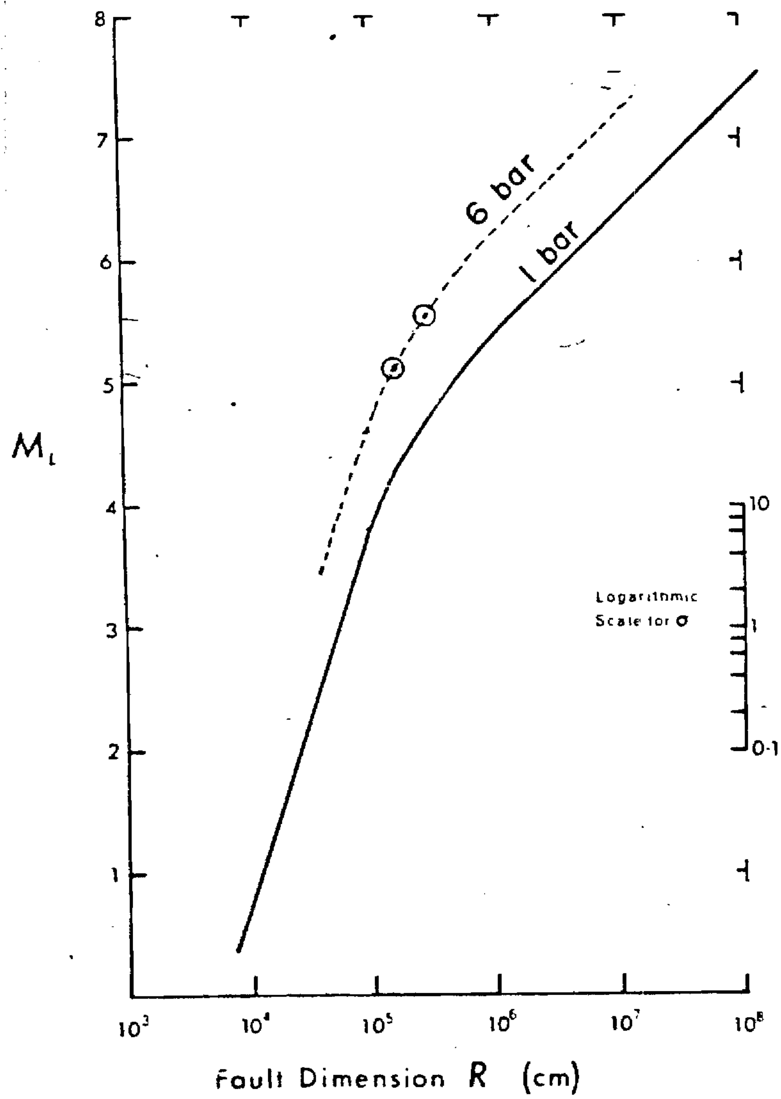

Figure 3. Randal's (1973) relations between local magnitude and effective fault radius adapted for a stress drop of 6 bars.

of 10 km^2 and 39.5 km^2 indicate maximum events of magnitude (M_L) 5.1 and 5.6 respectfully. The largest magnitude observed for a Piedmont Province earthquake is 5.45 (Long, 1977) and is consistant with the maximum plausible earthquake computed independently from stress drop considerations and plausible fault plane dimensions. The smaller dimensions indicated by individual activity zones in Jocassee area and by the geologic units prevalent in the CHRA would be typical of the magnitude 3.0 to 4.5 events more commonly observed in the Piedmont Province.

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ATTACHMENT II

Microearthquake Activity in the Piedmont Province

by L.T. Long

Introduction

The identification of many shallow microearthquakes near Jocassee Reservoir and the Clark Hill Reservoir raises the question of the general occurrance of these events throughout the Piedmont Province. In other words, "Would similar activity be recorded by arbitrarily placed stations?" The answer is in general that arbitrarily placed stations would not record similar activity. However, stations placed in known active areas and aftershock zones do record activity levels compatable with the historical activity of the area or the size of the main event. This can be inferred both from the evaluation of recording stations in the Piedmont and the generally understood character of earthquakes to occur in concentrated sperts or swarms in time and space. This is true for major faults where the activity over a short period will concentrate on a small portion of the fault and true also for less active areas where the earthquake mechanism is less well understood. Much of the low-level activity which has been observed can be explained as normal aftershock decay or induced (i.e. perturbed strength) seismicity.

Permanent Stations

The question of low-level seismic activity can be explored by first examining the experience of the existing permanent stations. Unfortunately the number of these stations which have operated in the southern Piedmont Province is small. These stations include ATL, CDG, CH5, CH6, JSC, and perhaps some other stations of the S.C. net. ATL has operated since 1963 and has perhaps one of the longest continuous records of seismic activity No events of natural origin have been identified as occurring within 25 km. The distance of 25 km. is perhaps the maximum distance that the small events considered here can be detected. Station CDG was established to monitor for possible seismic activity associated with the loading of the Carters Dam reservoir. The station CDG is located on the boundary between the Blue Ridge Province and the Folded Appalachians Province and thus is not strictly applicable to the question of seismic activity in the Piedmont Province. Nevertheless, only one event (and associated foreshocks and aftershocks) was detected and that event occurred in the Folded Appalachian Province. Stations CH5 and CH6 were established in the Clark Hill Reservoir area to monitor an area of known seismic activity. Station CH5 in the north has recorded events from the epicenter area of the August 2, 1974 earthquake. Station CH6 in the south has detected local activity amounting to an average of 4 to 10 events each six months. It is not known whether JSC and some other stations of the S.C.-net have recorded local activity. These data are being studied by the U.S.G.S. under the direction of Art Tarr.

Portable Station Surveys

A second way to answer the question as to the general occurrance of microearthquakes is to examine the records of seismic surveys using portable recorders. In the CHRA, an area of historic activity approximately 80 noise-free days of recording yielded approximately 8 events (see H.E. Denman, Masters Thesis, Georgia Institute of Technology 1974). This survey preceeded the August 2, 1974 earthquake but a number of magnitude 1.5 or greater events had been noted at ATL. An aftershock survey near Seneca yielded a small number of events within 15 km of the recording site (Long, BSSA vol. 64, #1, p. 267). Other attempts of aftershock studies have been less successful. Also, it should be noted that aftershock surveys must be considered inconclusive with respect to the general occurrance of microearthquakes since they are designed to study a known or suspected active area.

In 1974, Bollinger and Gilbert reported on "A Reconnaissance Microearthquake Survey of the Hot Springs, Virginia Area" (BSSA, vol. 64, #6, p. 1715). They totalled 440 hours of recording and identified only one 4-day swarm of 43 events recorded at only one station. They estimated the S-P at less than 0.2 sec. Ayers and Bollinger in a later study of microseismic and macroseismic ground motions in Virginia operated tape recorders which were operated for as long as two weeks duration at a single site and covered most of Virginia at a spacing of approximately 50 km. No microearthquakes were reported in their study.

In 1975, Bollinger (Earthquake Notes, Vol. 46, No. 1-2 pg. 3) reported on "A Microearthquake Survey of the Central Virginia Seismic Zone". The Central Virginia seismic zone is located largely in the Blue Ridge and Piedmont Provinces. The zone is an example of a transverse seismic zone exhibiting a low level of activity. Some 2200 low-noise hours of data were collected at 26 different locations throughout the zone. This monitoring program, complete down to about zero magnitude, recorded eight definite and four probably microearthquakes. This low rate of occurrance of one event every eight days seems to be in accord with the area's macroseismicity ($M \geq 3$) over the past 45 years. Of the 26 locations occupied only 7 recorded microearthquakes. Six of the eleven microearthquakes were assigned S-P times less than 0.4 seconds which makes them less than 3 km. away and questionable in origin since so few were identified.

G35-622-NUREG-0010

A GEOPHYSICAL INVESTIGATION OF THE SEISMICITY OF THE CLARK HILL RESERVOIR VICINITY

Quarterly Progress Report No. 8
December 1, 1976 - February 28, 1977

Leland Timothy Long
School of Geophysical Sciences
Georgia Institute of Technology
Atlanta, Georgia 30332

Report Date - March 15, 1977

PREPARED FOR THE U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH UNDER
CONTRACT NO. AT-(49-24)0210

A Geophysical Investigation of the Seismicity of the Clark Hill Reservoir Vicinity

Quarterly Progress Report No. 8

Abstract

Continuing seismic monitoring has been maintained for station CH5 and CH6, partial monitoring has been attained at RF recording sites. The data accumulated to date indicate a time variation in the regional distribution of activity. Spectral studies indicate that CHRA events typically have W^{-3} decay slopes at high frequencies and a ratio of P-wave to S-wave corner frequency equal to or greater than unity. These observations imply transsonic rupture velocities probably along existing lubricated surfaces. The refraction data have proved to be remarkably uniform.

Scope of Investigation

To use gravity, seismic refraction and other available geophysical data to study the structures fo the crust in the Clark Hill Reservoir Area and to relate the structures to earthquake activity as recorded by a telemetered array or by portable instruments. To initiate seismic monitoring of the Belair fault and of seismic activity near Lake Sinclair for similar studies of crustal structure and seismicity.

Results of Investigation During Quarter

Continuous seismic monitoring has been achieved for stations CH5 (Double Branches in the southern part of the reservoir) and CH6 (Goshen in the northern part of the reservoir). Of the four RF stations RF1, west of Goshen (CH6) has proved to be the most reliable. RF2, RF3 and RF4 have been received only sporatically. RF3 in the epicenter area had to be relocated because of logging activity. The RF stations have not detected significant activity. The previously located scattered activity occurred when the reservoir was anomalously low and activity stopped following return of the reservoir level to normal pool elevation. Consequently, our preliminary plans for the next quarter are to relocate all RF stations except RF1 to the August 1974 epicenter area and attempt focal mechanism studies with portable instruments and the RF data combined. A significant number of events have triggered our magnetic tape event recorder. These events are now being subjected to spectral analysis. We expect to generate a catalog of spectra for these larger microearthquakes (magnitude 0.0 to 1.5) as well as our developing catalogs of events recorded at CH5 and CH6.

During the quarter a talk was prepared for presentation at the Southeastern GSA meeting. An abstract is attached to this report. The talk also points out that the regional distribution of activity has changed with time. Prior to the August 1974 event and from about 2 years after the August 1974 event the activity has been scattered. During and for about 2 years following the August 1974 event the activity was concentrated in the aftershock zone implying that the main event may have perturbed the regional stress field.

Spectral evaluation of the larger events recorded at CH5 and CH6 has continued during the quarter. The spectral evaluation of microearthquakes recorded on portable tape recorders has been completed as a M.S. thesis by Mr. George E. Marion. This thesis will be rewritten for publication during the next quarter. The thesis contains a number of important results and descriptions of instruments used in studies of the CHRA and hence a copy is attached. Of particular interest is the high frequency trend of the CHRA and Jocassee Reservoir spectra (W^{-3}) which differs significantly from the W^{-2} slope for the Maryville Tennessee earthquakes. The ratio of P-wave to S-wave corner frequency for the Jocassee area were typically greater than unity, for CHRA events the ratio was near unity and for Maryville, Tennessee events for the ratio was less than unity. These observations imply transonic rupture velocities for CHRA and Jocassee events probably along existing surfaces whereas the Maryville events would be of subsmic rupture. The differences observed may prove to be fundamental differences between reservoir induced earthquakes (Jocassee and in part CHRA) and Tectonic events (Maryville, Tennessee and in part CHRA).

We have continued to obtain seismic refraction data from the R. B. Russell Dam site construction. The data will be analyzed by Mr. David Dunbar as a M.S. thesis. The analysis will include applications to understanding the local velocity anomalies and to improving the locations of earthquakes. To date, the data imply a remarkably uniform velocity profile considering the variations in the surface geology. Theoretical travel times computed from the preliminary model using ray path methods indicate a complex variation of travel time with depth for shallow (or distant) events. We hope to use the model to qualify and improve depth estimates for the microearthquakes.

In cooperation with the study by the U.S. Army Corps of Engineers concerning the R. B. Russell Project a magnetic survey of the epicenter area of the August 2, 1974 earthquake was performed. Final analysis is contigent on successful programming of an inversion method. Simple modeling confirms the existence of compositional zoning but has not yet revealed significant indications of faulting or anomalous features which can be associated with the earthquake activity.

Bibliography

GRAVITY ANOMALIES, GEOLOGY AND SEISMICITY IN THE CLARK HILL RESERVOIR AREA
LONG, Leland Timothy, School of Geophysical Sciences, Georgia Institute of Technology, Atlanta, Georgia 30332

A Bouguer Anomaly map of the Clark Hill Reservoir Area was compiled from over 1500 values with an average separation of 1.0 km. The map covers most of the reservoir area and includes 33° 37.5' to 34°N latitude and 82° 15' to 82° 37.5' W longitude. A geologic map compiled from available maps and limited field reconnaissance shows remarkable correlations with gravity anomalies. In particular, the granitic and mafic units are expressed as distinct negative and positive anomalies respectfully. Using surface geology as a constraint for density modeling, the major structures could be inferred. Seismic activity is predominantly in the northern part of the reservoir and concentrated primarily near the epicenter of the August 2, 1974 earthquake (33° 57' N, 82° 30' W) and more recently (September 1976) 10 km southwest. These epicenters are between a -16 mGal anomaly representing a granite to the northwest and a +12 mGal anomaly representing a mafic unit to the southeast. These epicenters do not appear to correlate with mapped faults or unique geologic units. Instead, the earthquakes may represent the release of stress related to major coherent structures in density or elastic properties. Stress concentration or amplification could be derived from the effects of inhomogenieties on regional stress or changes in strength induced by near surface phenomena.

G35-622-NUREG-0011

A GEOPHYSICAL INVESTIGATION OF THE SEISMICITY OF THE CLARK HILL RESERVOIR VICINITY

Quarterly Progress Report No. 9

March 1, 1977 - May 31, 1977

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Report Date June 15, 1977

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A Geophysical Investigation of the Seismicity of the

Clark Hill Reservoir Vicinity

Quarterly Progress Report No. 9

Abstract

Seismic monitoring has continued at stations CH5 and CH6 and at sites near the Belair fault and near Eatonton, Georgia. A gravity survey of the vicinity of the Belair fault area was also completed. A swarm of earthquakes occurred in the CHRA in April and field monitoring yielded sufficient data to give a composite focal mechanism solution. Movement occurred along a vertical plain striking N 60° W. The north side moved down. A source area for seismic activity near Lake Sinclair was located following a swarm of events identified at the Eatonton station. A new velocity structure for the CHRA has been used to improve the accuracy of event locations.

Scope of Investigation

To use gravity seismic-refraction and other available geophysical data to study the structures of the crust in the Clark Hill Reservoir Area and to relate the structures to earthquake activity as recorded by a telemetered array or by portable instruments. To initiate seismic monitoring of the Belair fault and of seismic activity near Lake Sinclair for similar studies of crustal structure and seismicity.

Results of Investigation During Quarter

The seismic monitoring has continued without major interruption at CH5 (Double Branches in the southern part of the reservoir) and CH6 (Goshen in the northern part of the reservoir). Short-term recording was achieved for the radio station RF1 and three radio stations in the epicenter area. However, these stations were pulled out in May to allow a design modification for improvement in signal quality. These stations will be installed in July. The station near Eatonton has operated nearly continuously and detected numerous events near Lake Sinclair.

Seismic monitoring of the vicinity of the Belair fault zone was initiated May 2, 1977. No local events have been detected. However, the site has a high noise level and if relocation does not improve the signal to noise ratio, the monitoring will be terminated in July. The field work and data reduction for the gravity survey in the Belair fault vicinity is complete. The gravity data will be compared to CHRA data for evaluation for possible similarities of the structures which are near the CHRA seismic activity and the Belair fault.

Spectral evaluation of the larger events was limited during the quarter since a graphical to digital converter will be available for use in early summer. Most of the effort was expended in preparing data for digitization and evaluating the calibration of the systems. This effort has resulted in a redesign of the system to provide improved tape-speed compensation. The few spectra which have been computed indicate results similar to those obtained by the portable instruments.

During April a small swarm of earthquakes occurred in the CHRA and this initiated three days of field monitoring. The data obtained were sufficient to allow a composite focal mechanism solution. The implied movement was on a fault plain striking N$60^{o} \pm 20^{o}$W with dip of 90 ± 10^{o} The northern block moved down. A compilation of focal mechanism solutions for the southeast United States is currently being prepared as a M.S. thesis by Mr. Stewart A. Guinn. Also during April two days of field monitoring data were obtained in the Lake Sinclair area following a small swarm of activity. This data allowed precise location of one event (33.2223, 83.2111, 0.89 km deep) in a remote area, 5 km north of the dam. The depth of focus and near-surface geology for this event is similar to results of the CHRA.

A catalog of events recorded at CH5 and CH6 has been kept up to date and this data is being compared to water level changes. The relation between activity rate and water level is complex but two tentative relations are emerging as consistent observations. The first is an increase in activity following a rapid rise in water level. The second (which also can explain the first observation) is an increase in activity with significant lowering of one reservoir level. The larger events and the August 2, 1974 earthquake are not distinguished by abnormalities in the water level. However, the extended aftershock sequence which followed the August 2, 1974 event could in part be explained by a gradual lowering of the water level.

A seismic refraction velocity study of the CHRA which is the thesis topic of Mr. David Dunbar has been completed. The data indicate a possible low velocity zone below three to five kilometers which imply that the metamorphosed rock near the surface is of higher velocity than the granites which lie under. At shallower depths the velocity versus depth structure has been interpreted as a smoothly varying function. Consequently, our location program has been modified to use the more-complex velocity structure and microearthquakes are being relocated. The average change in location is on the order of 10% when compared to locations computed from a constant velocity model.

Progress During Quarter

The project progressed at the scheduled rate during the quarter.

Efforts Expended During Quarter

The principal investigator expended an average of 25% time on the project during the quarter. One electrical engineering student was employed at about 60% time during the quarter. Three graduate students were employed at about 50% time during the quarter.

G35-622-NUREG-0012

A GEOPHYSICAL INVESTIGATION OF THE SEISMICITY OF THE CLARK HILL RESERVOIR VICINITY

Quarterly Progress Report No. 10

June 1, 1977 - August 31, 1977

Leland Timothy Long
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A Geophysical Investigation of the Seismicity of the Clark Hill Reservoir Vicinity

Quarterly Progress Report No. 10

Abstract

Seismic monitoring has continued at stations CH5 and CH6 and near Eatonton, Georgia. The BEL station northwest of Augusta was pulled out July 14, 1977. The site was noisy and no local events were detected. Both focal mechanism studies and microearthquake location studies indicate movement on two general orientations of fault planes. These are N80° $\pm$ 20E dipping steeply to the northwest and N60° $\pm$ 20°W dipping steeply to the southwest.

Scope of Investigation

To use gravity, seismic-refraction, and other available geophysical data to study the structures of the crust in the Clark Hill Reservoir Area and to relate the structures to earthquake activity as recorded by a telemetered array or by portable instruments. To initiate seismic monitoring of the Belair Fault and of seismic activity near Lake Sinclair for similar studies of crustal structure and seismicity.

Results of Investigation During Quarter

The seismic monitoring has continued without major interruption at CH5 (Double Branches in the southern part of the reservoir) and CH6 (Goshen in the northern part of the reservoir). Short-term recording was achieved for the radio station RF1. The three RF stations in the epicenter were removed in July (unfortunately two were vandalized). The three component systems from BEL will be installed in the epicenter area in September. The ETG station near Eatonton has operated nearly continuously and detected numerous events near Lake Sinclair.

Seismic monitoring of the vicinity of the Belair Fault zone was terminated July 14, 1977 because of noise and low activity level. No events were detected except for local quarry blasts. The gravity data for the Belair Fault Area has been reduced and subjected to numerical analyses.

Spectral evaluation of the larger events was discontinued until arrival of a graphical to digital converter in August, 1977. Softwave for the graphical to digital converter is expected to require about one month.

Additional evaluation of the focal mechanisms in the Clark Hill Reservoir Area was completed by S.A. Guinn as part of his M.S. thesis. The August 2, 1974 main event showed possible movement on a near vertical plane striking N80^{o} $\pm$ 20E with the north side moving down. A micro-earthquake on April 14, 1977 showed movement on a near-vertical fault plane striking N60^{o} $\pm$ 20^{o}W with the northeast side moving up.

All other events with identifiable first motions could be identified with one or the other of these focal mechanisms. Hence, faulting is occurring in the Clark Hill Reservoir Area on two or more planes. The main event focal mechanism corresponds to the general direction of the regional foliation of the rocks. The second mechanism corresponds to a prominent joint set in the epicentral area.

The Eatonton station recorded seventeen events during the quarter that could be located with the help of three other stations funded by Georgia Power. A plot of this preliminary location is enclosed. Unlike the CHRA events which tend to locate in discrete epicentral areas these epicenters appear scattered. Strong velocity anistropy in the region may partially explain this observation.

The catalog of events recorded at CH5 and CH6 has been kept up to date. Data will be abstracted from this catalog for submission to the "Southeastern U.S. Seismic Network Bulletin" currently being coordinated by Gil Bollinger. The activity level in the CHRA was abnormally low during the quarter amounting to less than five events in one month.

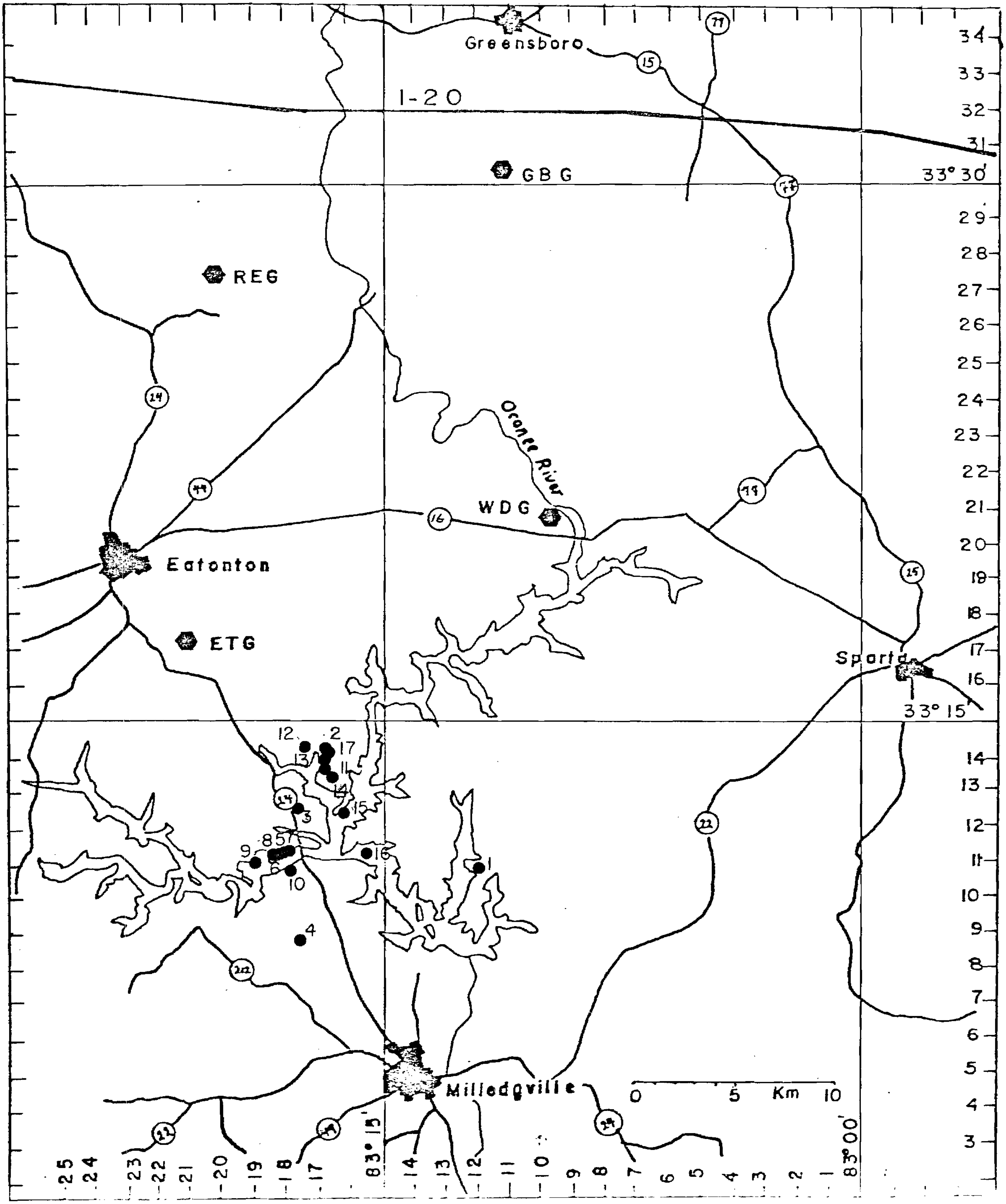
The seismic refraction study which was the thesis topic of David Dunbar is attached. A new hypocenter location method was developed to accommodate the unique velocity gradient in the CHRA. The method utilizes a table of travel times versus depth and distance to identify station-hypocenter pairs that provide significant depth control. The table is then used to generate derivatives required for the standard itterative least-squares solution. The new locations revealed two sets of planes compatible with the focal mechanism solutions mentioned above.

Progress During Quarter

The project progressed at the scheduled rate during the quarter.

Efforts Expended During Quarter

The principal investigator expended an average of 25% time on the project during the quarter. One electrical engineering student was employed at about 60% time during the quarter. Two graduate assistants were employed at about 50% time during the quarter.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